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THERMOMECHANICAL CHARACTERIZATION OF HASTELLOY-X UNDER UNIAXIAL CYCLIC LOADING

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INTRODUCTION

In most high-temperature engineering applications, components are subjected to complex combinations of thermal and mechanical loading during service. A number of viscoplastic constitutive models have been proposed which potentially can provide mathematical descriptions of material response under such conditions (refs. 1 to 9). Implementation of these models into large finite element codes such as MARC has already resulted in much improved inelastic analysis capability for hot-section aircraft engine components.

However, a number of questions remain regarding the validity of methods adopted in characterizing these constitutive models for particular high-temperature materials. One area of concern is that the majority of experimental data available for this purpose are determined under isothermal conditions. This is in contrast to service conditions which, as noted above, almost always involve some form of thermal cycling. The obvious question arises as to whether a constitutive model characterized using an isothermal data base can adequately predict material response under thermomechanical conditions.

An experimental program was initiated within the HOST program at the NASA Lewis Research Center to address this particular concern (ref. 10). This paper describes the results of the most recent isothermal and thermomechanical experiments.

EXPERIMENTAL DETAILS

The equipment and procedures used in the isothermal experiments have been described in detail previously (ref. 11). These experiments were conducted under uniaxial loading on closed-loop, electrohydraulic test systems. The specimens tested had a 1.25-in. parallel working section with a 0.313-in. outside diameter. Strains were measured over a 1.0-in. gage length using an axial extensometer. The specimens were heated using an RF induction heater and considerable effort was expended in achieving uniform temperature profiles over the gage length. Usually, temperatures fell within ±5 °C of the nominal test temperature throughout the experiments.

The method of test system control and data acquisition is shown schematically in figure 1. Axial strain is programmed to follow a triangular waveform provided by a Wavetek 175 function generator. The corresponding stress-time response is monitored using strip chart recorders until fatigue failure occurs. In addition,

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stress-strain hysteresis loops are recorded automatically at predetermined intervals using a Bascom-Turner recording system.

In the thermomechanical experiments, specimens were again heated using an RF induction heater. Specimen cooling was by means of the test system's water cooled grips. This was the preferred approach as it allowed temperature profiles to be maintained within acceptable limits during the cooling process. Also to assist in this regard, the gage length over which strain measurements were made was reduced to 0.5 in. in these experiments. The net result was that temperatures in the specimen's gage length were within ±10° C of programmed values during temperature cycling.

Another difference between the two sets of experiments is that a Data General S-20 computer was used for control purposes in the thermomechanical experiments. As indicated in figure 2, both axial strain and temperature were programmed to follow triangular wave forms, these waveforms being 180° out-of-phase in the subject experiments. As in the case of the earlier experiments, stress-time response was monitored until fatigue failure occurred. It is important to note that the same type of specimen, loading system, and heating system were used in the two series of experiments.

The material under investigation was Hastelloy-X in solution annealed condition. Two heats of material were obtained in 0.75-in. o.d. bar form meeting the requirements of Aerospace Material Specification (AMS) 5754H. As there was some question regarding the as-received condition of heat 1 material, specimens manufactured from this material were reannealed after fabrication and then micropolished to a surface finish of 8 rms. In the case of heat 2 material, reannealing and micropolishing was judged unnecessary. The as-machined surface finish of these specimens was 16 rms.

EXPERIMENTAL RESULTS

The results obtained in the isothermal experiments are shown in figures 3 to 6 as plots of stress range versus cycles. A logarithmic scale was selected for cycles as it allows the early stages of hardening, that occurring over the first 100 cycles, to be presented in a straightforward manner.

Another technique adopted to aid interpretation of the isothermal data was that of hardening curves determined at low, intermediate, and high temperatures were plotted separately. As indicated in figures 3 to 6, a single strain range, 0.6%, was used to generate the data presented here. Also as indicated, experiments conducted on Heat 1 material investigated a strain rate of 0.001 sec^{-1} while those conducted on Heat 2 material investigated strain rates of 0.001 and 0.0001 sec^{-1}.

In these exploratory experiments, no systematic attempt was made to investigate the repeatability of the data. However, in the experiments conducted at the slower strain rate, difficulties were encountered which meant that up to three attempts were necessary on occasion to successfully complete an experiment. The results of such repeat experiments are shown in figure 6 as they provide an indication as to the reproducibility of the isothermal data.

The results of six out-of-phase thermomechanical experiments are shown in figure 7. The method of data presentation is identical to that described above for the isothermal data. Clearly in this case, however, the cyclic hardening curves apply for temperature ranges rather than individual temperatures. Finally, thermomechanical and isothermal data determined at temperature in the range 400 to 600 °C (752 to 1112 °F) are compared in figure 8. These data were selected as they serve to highlight the differences in hardening behavior resulting from the two types of cyclic loading.

DISCUSSION

As a first step, the three sets of isothermal data were analyzed to establish general trends in the cyclic hardening behavior of Hastelloy-X. It was determined that individual hardening curves exhibit three types of hardening which will be termed early, transitional, and final in the following discussion.

In all three data sets, early hardening behavior, that occurring between cycles 10^0 and 10^2, is fairly systematic and repeatable. Over this cyclic range, hardening appears to be approximately linear in the plots shown in figures 3 to 5. The amount of hardening increases with temperature until reaching a maximum at 1200 °F (649 °C). At this temperature, the increase in stress range over the first hundred cycles is about double that occurring at the lower temperatures. As temperature is increased further, the amount of hardening decreases until at 1600 °F (871 °C) behavior is cyclically neutral. At still higher temperatures, the material exhibits small amounts of cyclic softening.

Material response during the transitional hardening stage is complex and almost certainly reflects aging processes occurring in the material during the experiments. In the case of heat 1 material, transitional hardening was evidenced between 10^2 and 10^3 cycles. In the tests conducted on heat 2 material, transitional behavior occurred over both earlier and later cyclic ranges. Up to 900 °F (482 °C), the slope of the hardening curves increase on the plots shown in figures 3, 4, and 5. At temperatures in the range 1000 to 1200 °F (538 to 649 °C), the hardening curves exhibit inflection points while at still higher temperature, the slopes of the hardening curves decrease.

Material response during the final stage of hardening is again more straightforward and is about linear on the semilogarithmic plots under discussion. Up to 1000 °F (538 °C), significant hardening is exhibited up to the point of fatigue failure. Between 1000 and 1200 °F (538 and 649 °C), hardening rates are drastically reduced which can result in the intersection of individual hardening curves. At higher temperatures, final hardening rates reduce until at 1600 °F (871 °C), behavior is essentially neutral.

It has already been noted that the cyclic hardening behavior of Hastelloy-X is complicated by thermal aging occurring during the experiments. This raises the possibility that some of the more subtle effects noted above might be sensitive to variations in the chemical composition of the material. Some feel for possible heat-to-heat variability can be obtained by comparing the heat 1 results shown in figure 3 with those for heat 2 shown in figure 4. Such comparisons show that the strain ranges achieved on the first cycle of the heat 1 experimental are less by about 100 MPa than those obtained in the heat 2 experiments. However, comparison of the two sets of curves shows that the general hardening characteristics of the two materials are very similar. The general trends of the data do not therefore appear sensitive to variability in material composition.

Questions also arise as to the role of strain rate in these isothermal experiments. Comparison of the data shown in figures 4 and 5 shows that cyclic hardening behavior at the two strain rates investigated is very similar up to 1300 °F (704 °C). Over this range, the rates of hardening in tests conducted at 0.0001 sec^{-1} are marginally higher than those obtained on tests conducted at 0.001 sec^{-1}. At higher temperatures, the most significant difference is that the stress range achieved on the first cycle of tests conducted at the slow rate are much reduced from those obtained at 0.001 sec^{-1}. Regardless of these first cycle differences, material response is essentially neutral at both strain rates for temperatures of 1600 °F (817 °C) and above.

One characteristic of the data which is of key concern to the experimentalist is that of repeatability. This is particularly the case when particular combinations of variables are characterized by single experiments only. The data shown in figure 6 provides some insight as to repeatability at least during the early and transitional stages of hardening. The most significant difference between repeated experiments is in first cycle response. Subsequently, the hardening behavior is very similar in the repeat experiments. At particular numbers of cycles into the test, stress ranges fell within about ±25 MPa of the mean. This is equivalent to percentage deviations of the order of ±5% for stress ranges around 500 MPa.

Having established a fair degree of confidence in the validity of the isothermal data base, the final and most important question addressed was what if any of the trends noted above carry over to thermomechanical conditions. As noted earlier, this is a major concern since service conditions usually involve thermomechanical loadings whereas the data usually available for material characterization is determined in isothermal experiments. A partial answer to this question can be obtained by comparing data shown in figures 5 and 7. At temperatures up to 900 °F (482 °C), the early hardening rates in the thermomechanical experiments can be seen to be about twice those obtained in isothermal experiments conducted over the same range of temperatures. The situation in the thermomechanical test conducted over the temperature range 400 to 600 °C (752 to 1112 °F) is somewhat different, as indicated in figure 8. Here, the early hardening behavior is similar for the two types of loading but the transitional and final stages differ significantly. Specifically, the hardening in the thermomechanical test is about three times that of the isothermal experiments. Clearly, the thermomechanical result could not have been predicted given the isothermal data shown. At temperatures above 1300 °F (704 °C), the isothermal and thermomechanicl results are similar. Thus, at these temperatures, the feasibility of predicting the thermomechanical results from an isothermal data base appears more practicable.

CONCLUSIONS

The following conclusions were drawn from the study of cyclic hardening in Hastelloy X under isothermal and thermomechanical conditions.

1. Cyclic hardening under isothermal conditions ranges from modest hardening, to drastic hardening, to modest softening as temperature increased. This highlights the importance of covering the entire temperature range of interest in characterization studies.

2. Cyclic hardening under isothermal conditions is extremely complex at temperatures in the range 1000 to 1200 °F (538 to 649 °C). At both higher and lower temperatures, behavior is less complex and it appears likely that the data can be modeled using fairly simple mathematical representations.

3. Cyclic hardening under isothermal conditions is not particularly sensitive to heat-to-heat variations and to strain rate effects, at least over the range 0.001 to 0.0001 sec^{-1}. Also, in terms of general hardening characteristics, the data are fairly repeatable.

4. Cyclic hardening under thermomechanical conditions differs significantly from that obtained in isothermal tests up to temperatures of about 600 °C (1112 °F). The hardening rates in the thermomechanical tests are factors of 2 and above greater than those obtained in isothermal experiments.

5. Cyclic response at temperatures above 600 °C (111 °F) is similar under both isothermal and thermomechanicl loading. In the limit, both types of loading exhibit behavior that is essentially cyclically neutral. Clearly under these conditions, an isothermal data base can be used more reasonably to model thermomechanical response.

FUTURE WORK

The emphasis of future testing will be in generating a more complete thermomechanical data base for Hastelloy X. Presently, experiments are being conducted under uniaxial loading over temperature ranges of 400 °C and this will be extended in later experiments to 800 °C. Also, it is planned to extend the investigation to the torsional form of loading. The advantage here is that apparent strains due to thermal expansion are second order effects in torsional strain measurements and so do not complicate interpretation of the data.

One deficiency of the data discussed in this paper is that it is presented entirely in the form of stress range versus cycles. Adopting this simplistic approach, no consideration is given to the inelastic material response which is occurring at various stages of individual cycles. This situation is being corrected by the use of more efficient data acquisition systems. Procedures are being developed which will allow the data to be reduced in a form more consistent with theoretical developments.

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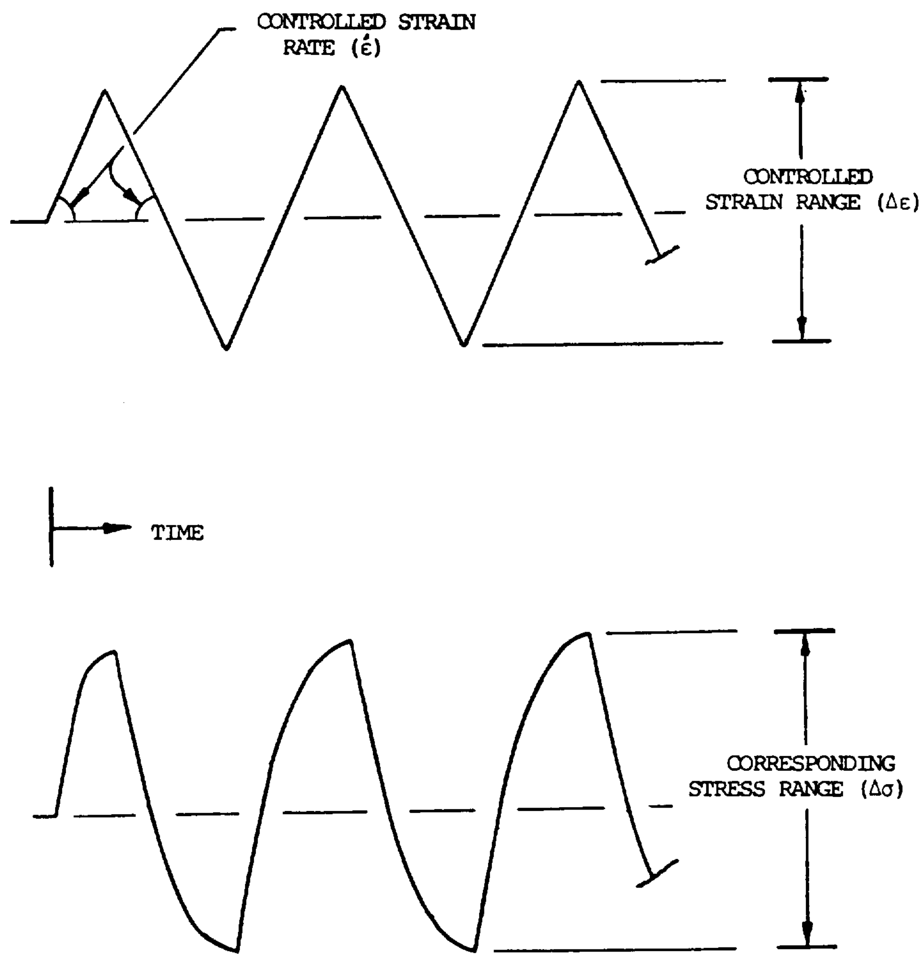

FIGURE (1) METHOD OF TEST SYSTEM CONTROL AND DATA ACQUISITION IN ISOTHERMAL EXPERIMENTS .

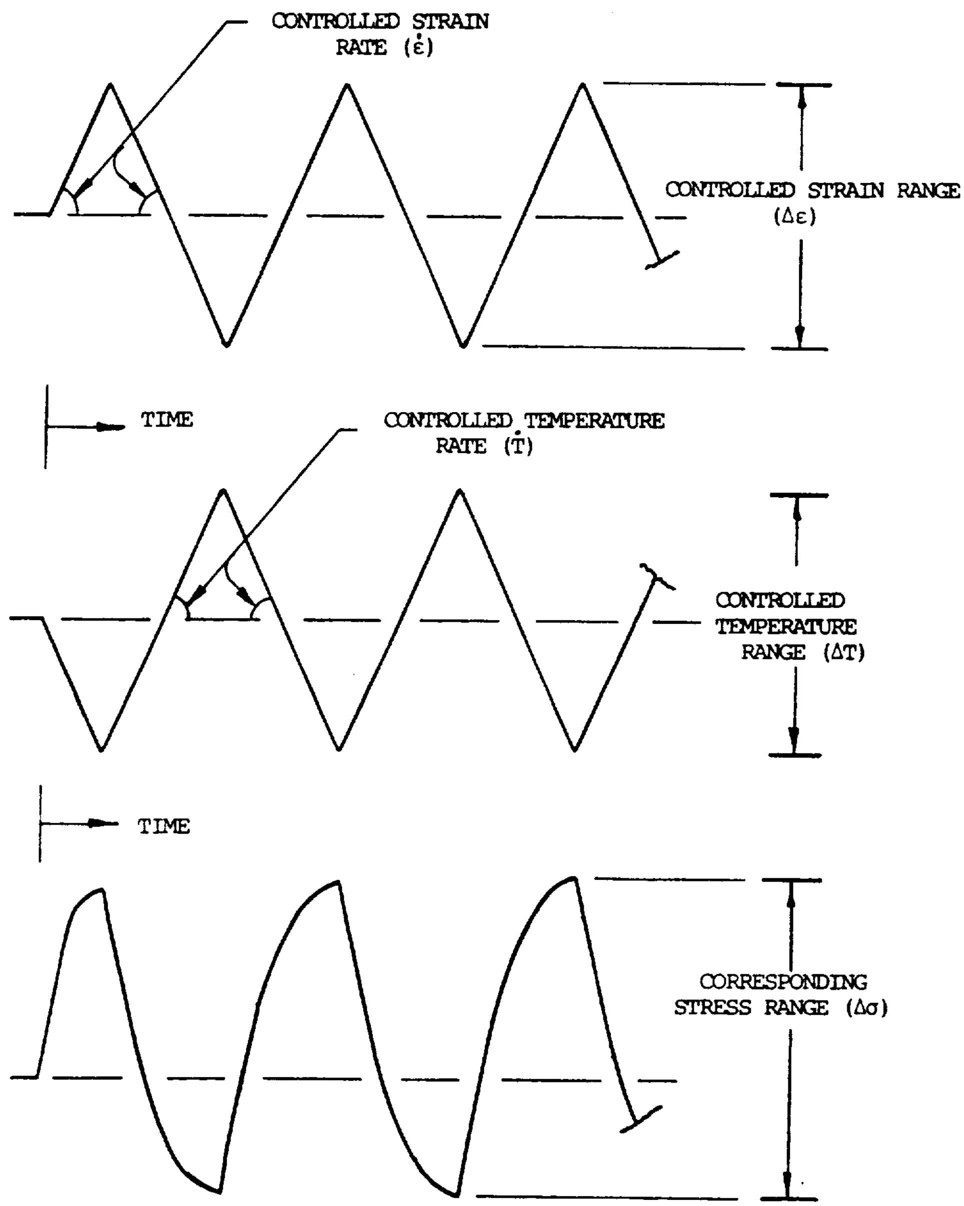

FIGURE (2) METHOD OF TEST SYSTEM CONTROL AND DATA ACQUISITION IN OUT-OF-PHASE THERMOMECHANICAL EXPERIMENTS.

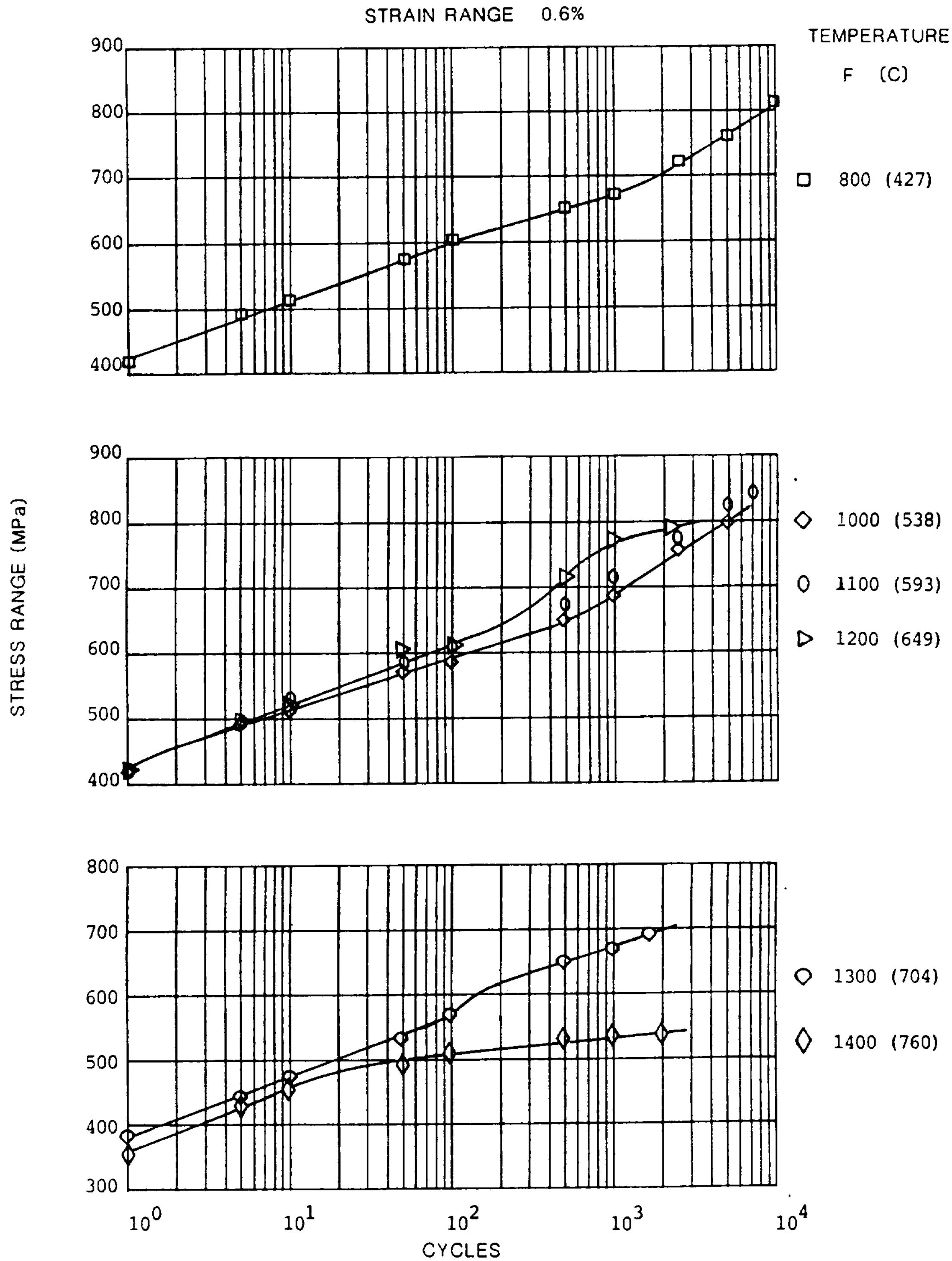

FIGURE (3) RESULTS OF ISOTHERMAL TESTS CONDUCTED ON HEAT (1) MATERIAL AT A STRAIN RATE OF 0.001/sec.

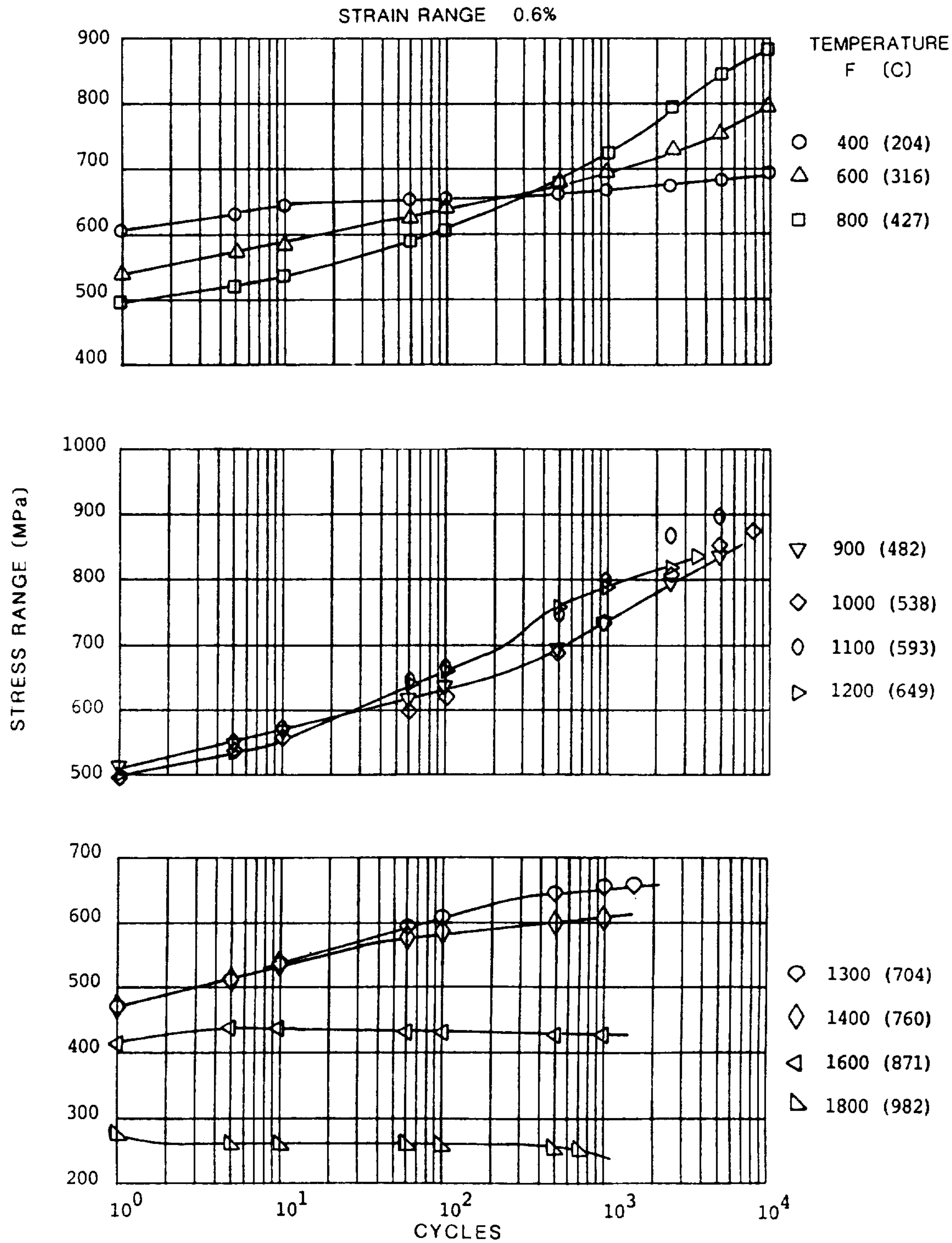

FIGURE (4) RESULTS OF ISOTHERMAL TESTS CONDUCTED ON HEAT (2) MATERIAL AT A STRAIN RATE OF 0.001/sec.

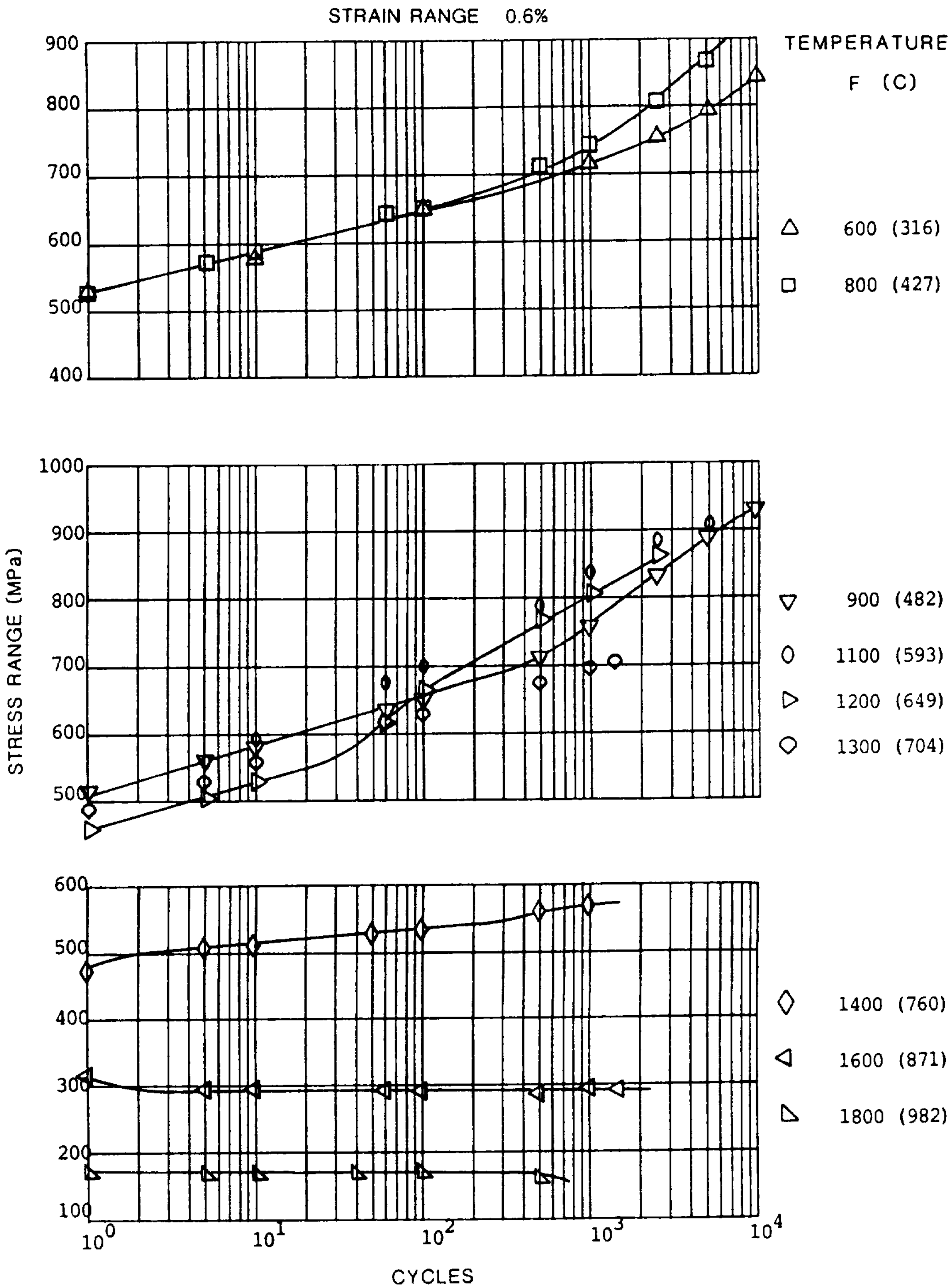

FIGURE (5) RESULTS OF ISOTHERMAL TESTS CONDUCTED ON HEAT (2) MATERIAL AT A STRAIN RATE OF 0.0001/sec.

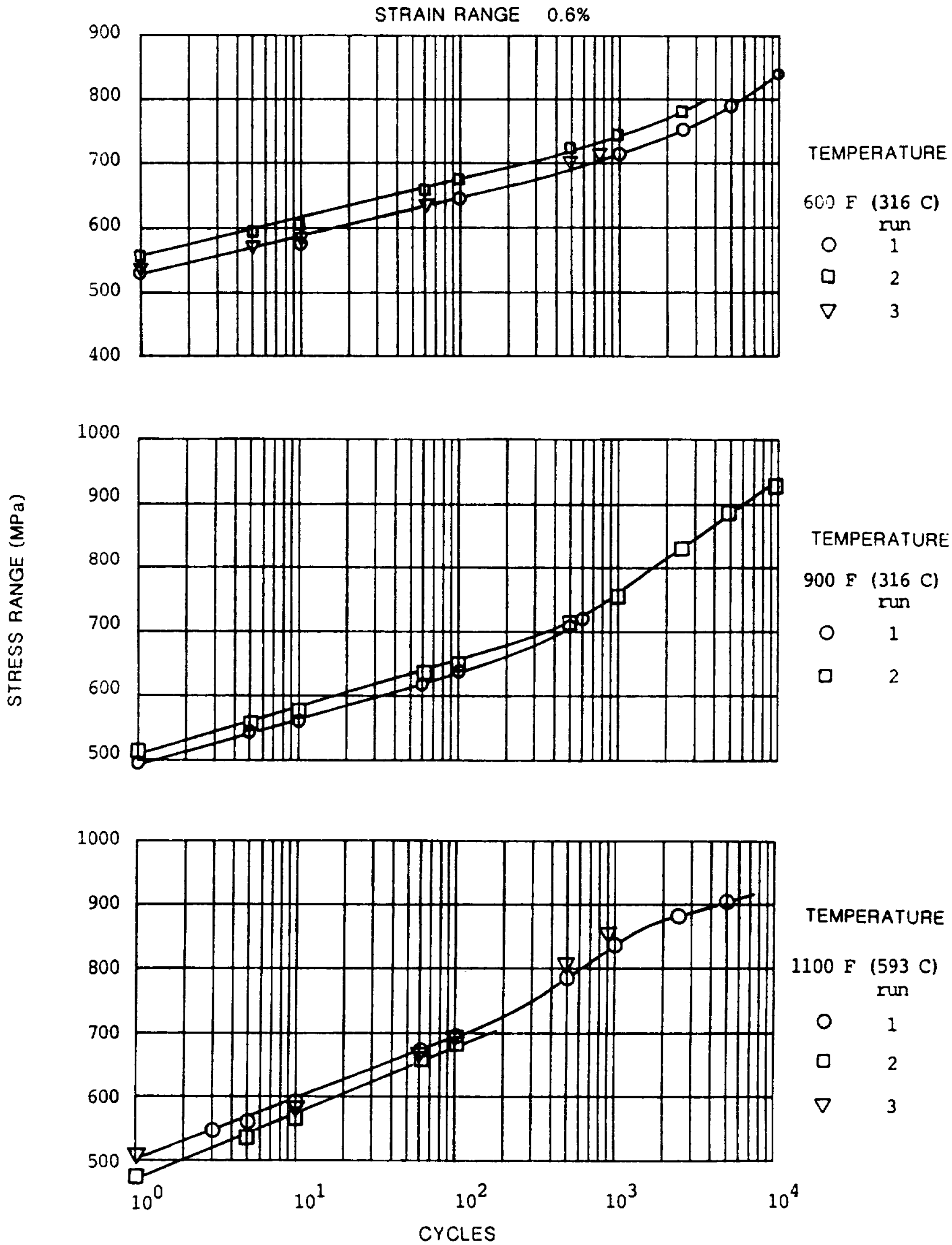

FIGURE (6) RESULTS OF REPEAT EXPERIMENTS CONDUCTED ON HEAT (2) MATERIAL AT A STRAIN RATE OF 0.0001/sec.

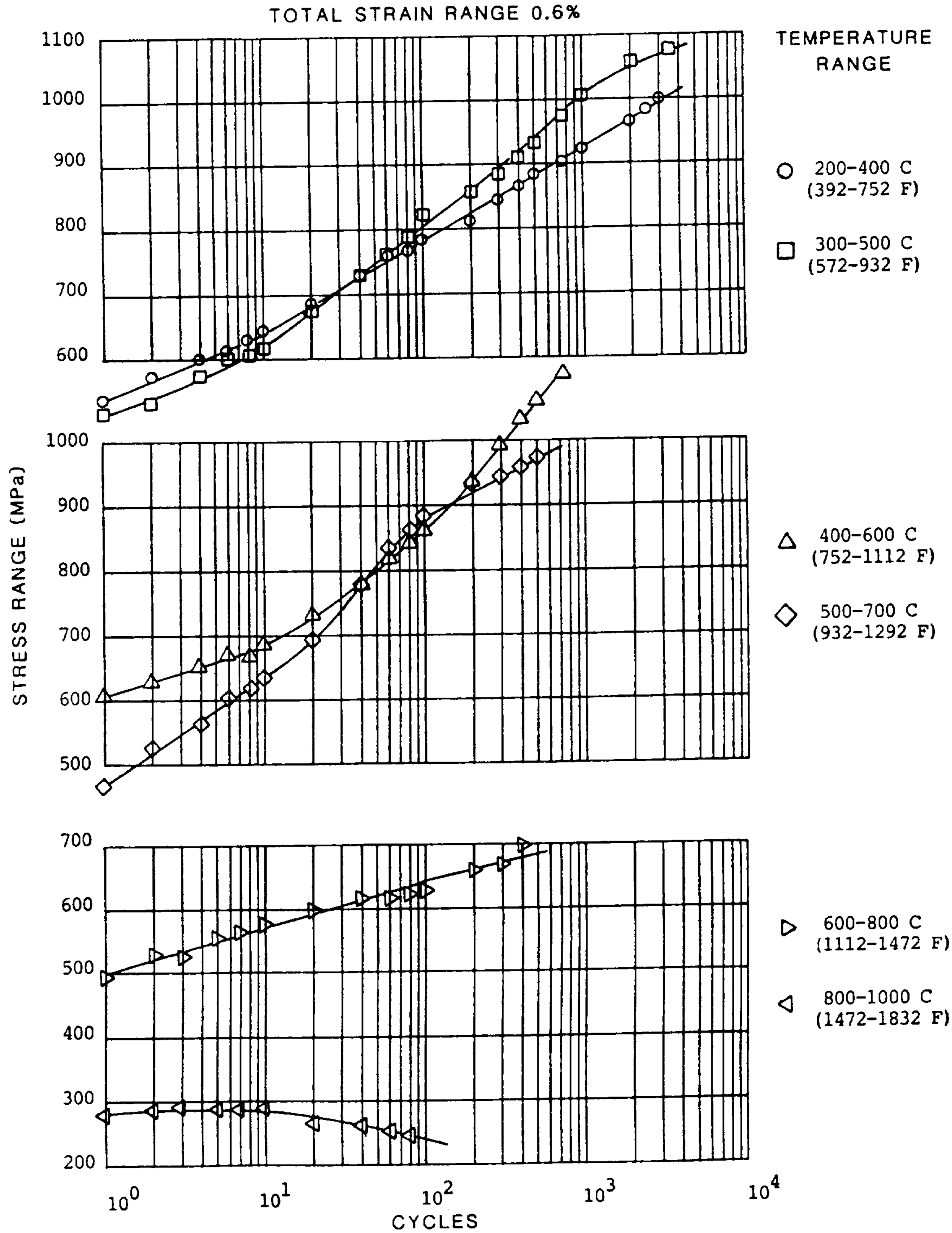

FIGURE (7) RESULTS OF OUT-OF-PHASE THERMOMECHANICAL TESTS CONDUCTED ON HEAT (2) MATERIAL AT A STRAIN RATE OF 0.00005/sec.